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Planning for the Development of a 40 kWp Off-Grid Centralized Solar Power Plant (SPP) on Insumbabi Island

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Abstract

This study aims to design and evaluate a 40 kWp off-grid centralized Solar Power Plant (SPP) to meet the electricity needs of two underserved villages on Insumbabi Island, Supiori Regency, Papua, Indonesia. A systematic planning and technical design process was conducted, comprising field surveys, satellite-based solar potential analysis, load assessment, and system configuration. Performance simulations using photovoltaic (PV) Syst software indicate a daily energy output of 158.386 kWh, delivered by 216 PV modules and battery storage with two-day autonomy. The system achieves an annual average production of 3.3–3.6 kWh/kWp/day. The maximum energy that can be produced by the solar panels reaches 67,661 kWh per year, with the highest monthly output of 6,194 kWh in August and the lowest of 4,992 kWh in February, a performance ratio (PR) of 0.602, and a solar fraction (SF) of 1.0. This confirms its capacity to fully meet local energy demands year-round. The proposed design demonstrates high feasibility and offers a replicable model for off-grid rural electrification projects in Indonesia.

Keywords: solar, insumbabi, electric, energy.

1. Introduction

Currently in Indonesia, most electrical energy networks are only available in large cities or regions with relatively high population density and good access to public transportation. In contrast, people living in remote areas or scattered across small islands far from public transportation remain unreached by the electricity grid [1]. Difficult access and logistics to these locations significantly increase the investment cost for electricity grid expansion or conventional power plant construction, compounded by high operational and maintenance costs due to transportation challenges [2].

According to the electrification ratio report from the Directorate General of Electricity, Ministry of Energy and Mineral Resources, as of June 2017, Indonesia's electrification ratio reached 92.80%. This means that approximately 5.87 million households in Indonesia still do not have access to electricity from the Perusahaan Listrik Negara (PLN) grid [3]. In addition to electrification issues in remote areas, the Indonesian government has also set a target through the National Energy General Plan (RUEN) to achieve a 23% renewable energy mix by 2025. As of 2017, the renewable energy mix in Indonesia was only 12.5%, with an increase of only 2% over the past three years. This is still a very small figure considering that 2025 is only a few years away [4].

Utilizing renewable energy is essential for maintaining future energy security. It reduces dependence on fossil fuels by replacing them with inexhaustible natural energy sources such as water, sunlight, wind, ocean, waste, and biofuels [5]. A centralized Solar Power Plant (SPP) is one alternative solution to provide electricity in remote areas. This SPP is a form of renewable energy that harnesses abundant free solar energy and converts it into electricity [6]. The system can generate and store electrical energy, making it reliable for supplying power both day and night. The implementation of centralized photovoltaic solar power as an alternative electricity source in remote areas is very appropriate, especially considering Indonesia is located along the equator and receives abundant sunlight. The average solar energy potential in Indonesia is relatively high, at approximately 4.80 kWh/m^2/day [7].

In this study, notable differences emerge when compared to previous research on renewable energy applications: the investigation conducted in Sumba Jaya, East Nusa Tenggara, employed a hybrid system integrating wind power plants and was simulated using the HOMER software [2]. Meanwhile, a similar study in Kyrgyzstan was relied on statistical data modeling and historical data analysis to assess renewable energy potential in remote areas [8]. A study of off-grid solar photovoltaic (PV) systems was carried out in Bungku Village, focusing on their use for orchard lighting without performing simulations in PVsyst software, and employing a field-based descriptive research approach [9].

To meet the electricity needs of the local community, a power plant must be established on Insumbabi Island, specifically in Insumbabi Hamlet, Aruri Islands District. The proposed power plant should be practical, easy to operate, require no moving components that incur high maintenance costs, and utilize free natural energy. The selected power plant is a SPP as Insumbabi Island has a solar energy potential of 3.662 kWh/kWp per day [10]. The implementation of this SPP is expected to improve the standard of living for residents of Insumbabi Hamlet and Insumbabi Island in general. Additionally, it supports the government's policy to reduce dependence on fossil fuels by transitioning to inexhaustible natural energy sources [11].

2. Experimental Methods

The methodology for designing the 40 kW SPP system follows a four-stage procedure:

1. Site survey & data collection: Conducting on-site measurements to record load profiles from residential and public facilities. Acquiring local solar irradiance and climatology data from the Global Solar Atlas [12].
2. Load analysis: Calculating daily energy requirements by aggregating individual load demands (households, school, church, health center, village hall, street lighting, and small businesses). Including a 25% reserve margin and account for 15% system losses to determine total energy consumption [9].
3. System sizing:
   a. PV array design: Determining the number of PV modules, their tilt angle (3°), and orientation (north) to optimize irradiation absorption. Calculating required peak array capacity based on total daily demand and average irradiance.
   b. Battery specification: Sizing battery bank for two days of autonomy, selecting 2 V, 1000 Ah VRLA cells configured into series and parallel strings to meet the daily energy reserve.
   c. Power electronics: Selecting inverter capacity and number of units to handle peak load plus safety margins. Calculating charge-controller current rating based on PV array peak power and system voltage.
4. Performance simulation: Validating the designed configuration using PVsyst software. Simulating annual energy yield, performance ratio (PR), and solar fraction (SF) to ensure system can meet 100% of demand under real-world conditions.

The applied method includes direct data collection through field surveys during the planning stage, followed by manual system design and performance simulation using PVsyst software to achieve optimal and realistic results [13].

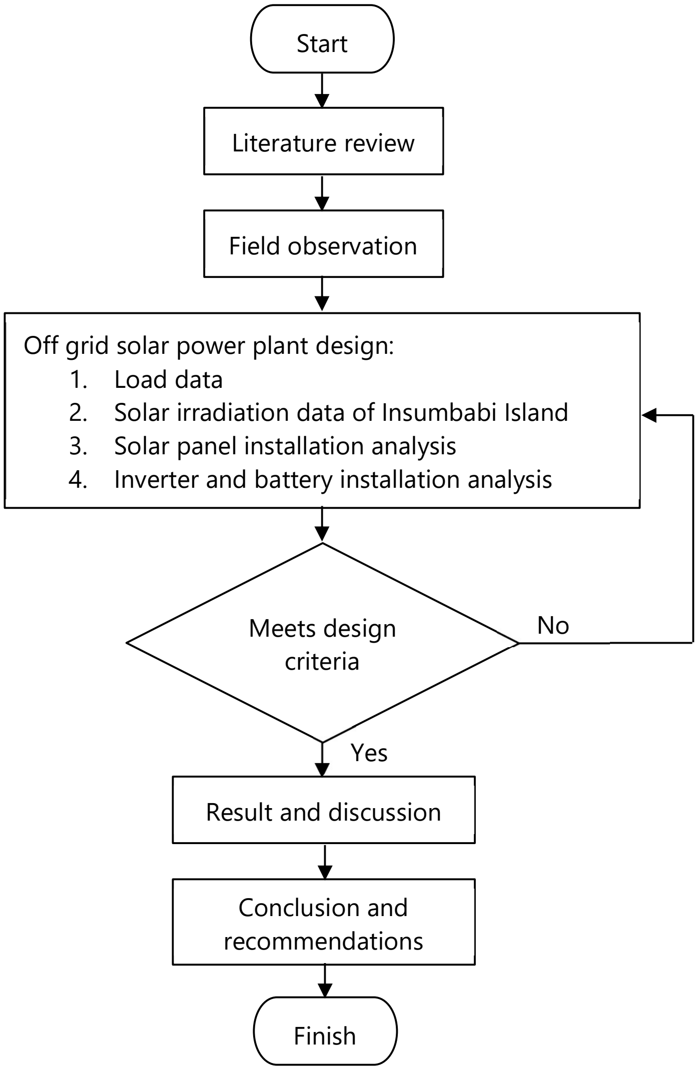


Figure 1. Activity Flowchart

Figure 1 represents summarizing activity in the present study. According to Figure 1, the research step is as follows.

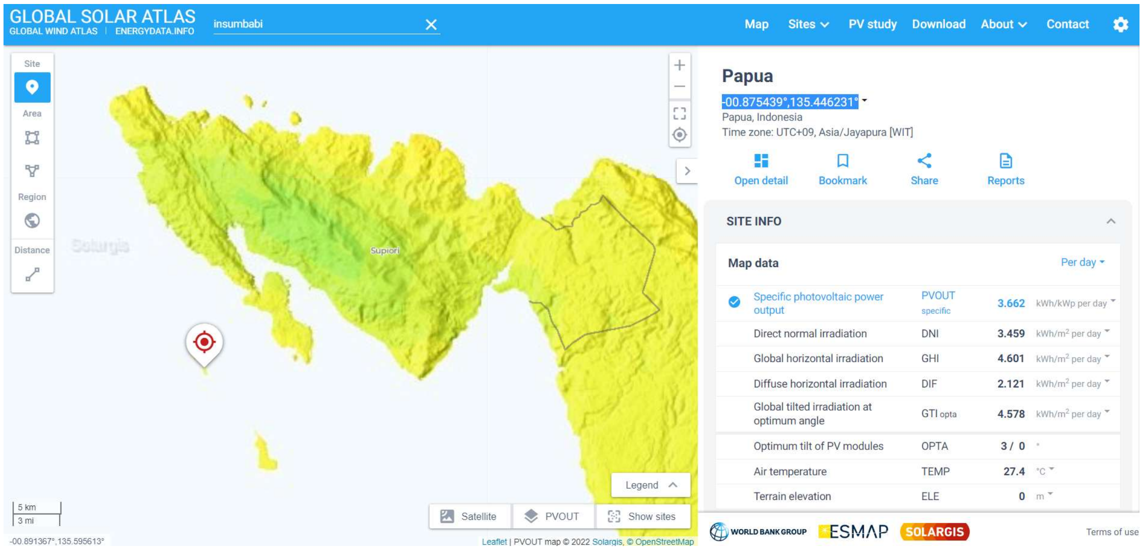
2.1. Literature Review

The literature review in this study refers to sources related to renewable energy, particularly solar energy applications. The references include calculations of the optimal sun angle relative to solar panels, analysis of the most suitable conditions for specific locations, and the selection of panel materials such as thin-film solar cells, polycrystalline silicon, and monocrystalline silicon based on solar irradiance absorption [14]. In the design of the SPP, mathematical equations are used to calculate power requirements, the number of panels, and the number of batteries. Additionally, satellite data is utilized to obtain local climate information, such as temperature and solar irradiance potential in the Insumbabi Island region [15].

2.2. Field Observation

Insumbabi Island is located at coordinates -0.877778° latitude and 135.411111° longitude, indicating a location in the Papua region of Indonesia. It lies slightly south of the equator and is situated in the eastern hemisphere. The negative sign in the latitude denotes a position in the southern hemisphere, while the longitude of 135.411111° indicates its location east of the Greenwich meridian [16]. This area falls within the Eastern Indonesia Time Zone (WIT) with a UTC offset of +09, corresponding to the Asia/Jayapura time zone. Its proximity to the equator results in high solar irradiance throughout the year, providing significant potential for solar energy development [11].

To assess solar energy potential, satellite-based and modeling platforms such as the Global Solar Atlas (https://globalsolaratlas.info/map) by Solargis can be used, as illustrated in Figure 2 below.



Papua
-00.875439°,135.446231°
Papua, Indonesia
Time zone: UTC+09, Asia/Jayapura [WIT]

SITE INFO

Map data — Per day

Specific photovoltaic power output	PVOUT specific	3.662	kWh/kWp per day
Direct normal irradiation	DNI	3.459	kWh/m^2 per day
Global horizontal irradiation	GHI	4.601	kWh/m^2 per day
Diffuse horizontal irradiation	DIF	2.121	kWh/m^2 per day
Global tilted irradiation at optimum angle	GTI opta	4.578	kWh/m^2 per day
Optimum tilt of PV modules	OPTA	3 / 0	°
Air temperature	TEMP	27.4	°C
Terrain elevation	ELE	0	m

Figure 2. Solar energy potential based on the global solar atlas

From the site, solar irradiation potential data for the output power of the SPP on Insumbabi Island was obtained, showing a value of 3.662 kWh/kWp/day with an optimal tilt angle of 3° facing north.

2.3. Load Consumption

The SPP on Insumbabi Island is designed to meet the electricity needs of two villages, covering the following facilities:

a. Residential houses : 82 units
b. School : 1 Unit
c. Church : 1 Unit
d. Village hall : 1 Unit
e. Auxiliary health center : 1 Unit
f. Small business unit : 1 Unit
g. Public street lighting : 1 Unit

According to the Ministry of Energy and Mineral Resources Regulation No. 3 of 2017, the primary electricity needs of the community served by the SPP for household and public facility lighting are limited as follows:

a. Energy per household: 1,600 Wh/day
b. Energy per school: 2,000 Wh/day
c. Energy per church: 2,500 Wh/day
d. Energy per auxiliary health center: 3,200 Wh/day
e. Energy per village hall: 3,000 Wh/day

f. Energy per small business unit: 11,200 Wh/day
g. Energy per public streetlight: 560 Wh/day
h. A 15% energy reserve to accommodate future household connections and equipment derating
i. System losses estimated at 5%

The usage duration is adapted based on the load type and energy parameters. The following Table 1 presents the planned daily energy demand for the Insumbabi Island SPP:

Table 1. Energy Requirements of Insumbabi Island

No.	Load type	Number of units	Energy requirement per unit (Wh)	Total daily energy (Wh)
1	Residential Houses	82	1010	82.820
2	School	1	480	480
3	Church	1	906	906
4	Auxiliary Health Center	1	936	936
5	Village Hall	1	1896	1896
6	Public Street Lighting	16	360	5760
7	Small Business Units	2	8736	17.460
Sub Total				110.272
Energy Reserve 25%				27.457
Subtotal + Reserve				137.727
System Losses				20.659
Total				158.386

Based on Table 1 above, a load consumption curve for Insumbabi Island can be generated as shown in Figure 3 below.

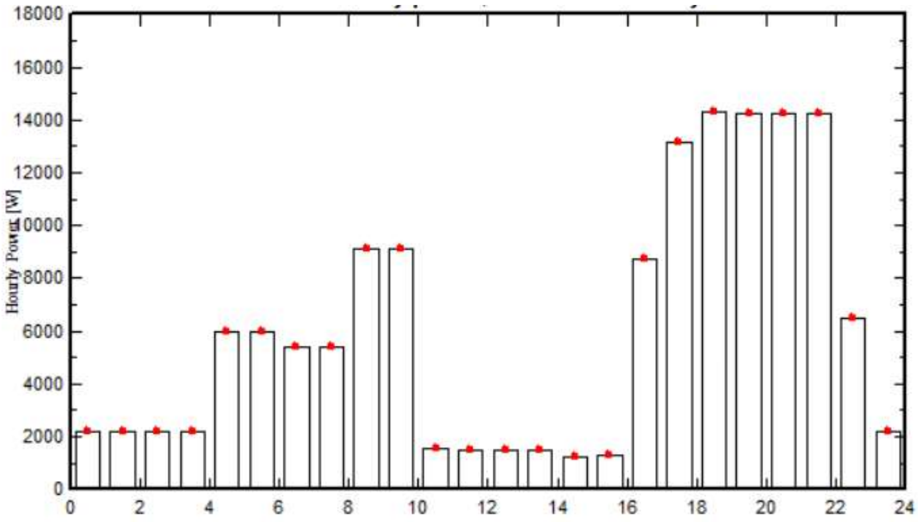


Figure 3. Forecasting load consumption

From Table 1 and Figure 3, the total energy required by the Insumbabi Island SPP is 158,386 Wh/day. The maximum installed load is 11,232 W. By considering a 25% reserve margin and 15% system losses, the peak load is estimated at 14,240 W, occurring between 18:00 and 21:00 WIT.

2.4. Solar Panel Installation Analysis

The capacity of the solar module is calculated based on the following data:

a. Daily energy requirement = 158.386 Wh/day
b. Average daily solar irradiance = 3.682 kWh/m^2
c. Solar module efficiency = 16%
d. Module output power = 200 Wp

Calculation:

Peak power of solar modules $= \frac{kWh}{(Average\ Daily\ Radiance)}$ (1)
= 158.386 / 3,662
= 43kWp

Effective area required $= \frac{kWp}{(Module\ Eficiency)}$ (2)
= 43kWp / 16%
= 270 m^2

This effective area represents the surface area required by the modules themselves, excluding spacing for module arrangement, installation, maintenance, fencing, and other structural considerations. To accommodate these components, the calculated area needs to be doubled.

Total area required $= Effective\ Area$ x 2 (3)
= 540 m^2

Number of modules $= \frac{(Total\ Peak\ Power)}{(Module\ Output\ Power)}$ (4)
= 43.000 Wp/ 200 Wp
= 216 Unit

2.5. Battery Capacity Calculation

After determining the number of solar modules needed, the next step is to calculate the required battery capacity. The data required includes the number of autonomy days, which is determined based on local cloud conditions. If the area is frequently overcast (typically in mountainous regions), it is recommended to use three days of autonomy in the calculation. If the area experiences relatively clear weather throughout the year, one to two autonomy days is sufficient. In addition, the DC voltage and battery specifications must also be considered.

Data:

a. Total daily energy demand with reserve & Losses = 158.386 Wh/day
b. Number of autonomy days = 2 days
c. System voltage (Vdc) = 48 V
d. Battery capacity (unit) = 1000 Ah, 2V
e. Minimum cycle life = 2200 cycles at 80% depth of discharge (DOD)
f. Battery type: Valve Regulated Lead Acid (VRLA) dry battery (OpzV) or deep-cycle Zinc-Air / Lithium-Ion

Thus, the required battery energy is calculated as follows:

Battery energy requirement $= (Total\ Daily\ Energy\ Demand\ \&\ Losses\ x\ Autonomy\ Days\ )$ (5)
= 158.386 Wh/day × 1.7 days
= 269.257 Wh

Battery requirement:

Number of batteries in series

$$= \left(\frac{(System\ Voltage)}{(Battery\ Unit\ Voltage)} \right) \quad (6)$$

= 48Vdc / 2Vdc
= 24 Unit

Parallel configuration

$$= \left(\frac{(Total\ Daily\ Energy\ Demand)}{((Battery\ Unit\ Voltage \times System\ Voltage \times Battery\ Capacity \times DOD)} \right) \quad (7)$$

= 158.386 / (60 x 1000 x 0.8)
= 6 parallel battery strings

Total number of batteries

$$= \ (Number\ in\ Series\ \times\ Number\ in\ Parallel) \quad (8)$$

= 24 × 9
= 216 Units

2.6. Inverter Capacity Calculation

The inverter is used to convert DC power into AC power, which will be transmitted through the distribution network. The capacity and number of inverter units are calculated based on the following:

Data:

a. Maximum load power capacity = 11.232 watts
b. Inverter power rating = 6.800 watts
c. Reserve margin dan losses = 25% and 15%

Calculation:

Inverter capacity = Peak Load + (Peak Load × Reserve Margin × Losses) (9)
= 11.232 +(17.342 × 25% × 15%)
= 14.240 VA

Number of inverter units:

$$= \frac{Inverter\ Capacity}{Inverter\ Power\ Rating} \quad (10)$$

= 14.240 / 6800
= 3 Units

2.7. Solar Charge Controller (SCC) Requirement Calculation

The power and current capacity of the Solar Charge Controller is calculated based on the following:

Data:

Peak power of solar modules = 43.000 Wp
System voltages = 48 Volts
Selected SCC unit current capacity = 75 Amperes / Unit

Calculation:

Total SCC Current = Peak Power / System Voltage (11)
= 43.000 / 48
= 895 Amperes

Power capacity per SCC unit = Peak power / Number of SCC Units (12)
= 895 / 75
= 12 Units

Power capacity per SCC unit = Peak power / Number of SCC Units (13)
= 43.000 / 12
= 3.500 W or greater

3. Results and Discussion

Based on the processed data, validation was carried out using PVsyst software to simulate the energy production and PR of the 40 kW off-grid SPP in Insumbabi.

3.1. Normalized Productions (per installed kWp)

In this subsection, we present the monthly averages of daily specific energy production (kWh/kWp/day) from the Insumbabi off-grid solar PV system a full year of operation, with the results classified into four key components—energy supplied to the user (Yf), PV array losses (Lc), system losses including battery charging (Ls), and unused energy due to full battery capacity (Lu). As shown in Figure4, the user-supplied energy (Yf) dominates during the dry months, the monthly average electricity production ranges between 3.3 and 3.6 kWh/kWp/day, while Lc remain relatively low and stable throughout the year. In contrast, system and Ls increase during periods of high irradiance fluctuations, indicating the impact of conversion inefficiencies, and the unused energy component (Lu) becomes significant in months where battery capacity is exceeded—highlighting times when excess generation cannot be stored. Together, these trends in Figure4 demonstrate how both environmental conditions and storage limitations influence the overall performance of the off-grid system.

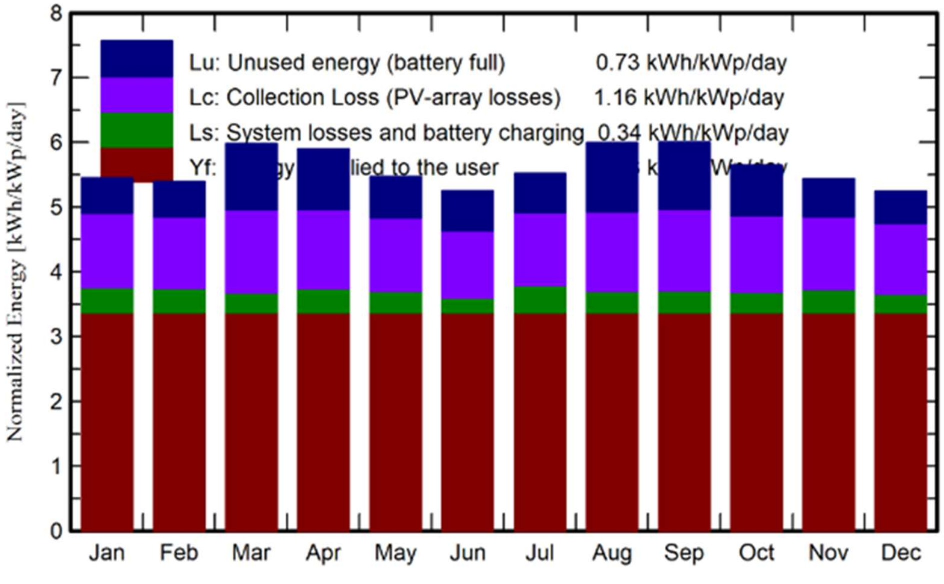


Figure 4. Solar energy output per kWp installed

Based on Figure 4 represented by red bars, the output remains relatively stable and consistent throughout the year. The highest energy supplied to users occurs in August and September, reaching approximately 3.6 kWh/kWp/day. These months fall within Indonesia's dry season, during which solar irradiance tends to be optimal, resulting in increased electricity production from the PV system. Conversely, the lowest production is observed in December at around 3.3 kWh/kWp/day, coinciding with the onset of the rainy season, which reduces daily solar energy generation.

Lc, shown in purple, remain relatively constant throughout the year, ranging from 1.1 to 1.2 kWh/kWp/day, with an annual average of 1.16 kWh/kWp/day. This indicates that approximately 20–22% of available energy is lost due to suboptimal panel performance, which may be caused by high temperatures, dust accumulation, or partial shading of the modules.

System losses and Ls, indicated in green, contribute minimally to total daily energy output, ranging between 0.3 and 0.4 kWh/kWp/day, with an annual average of 0.34 kWh/kWp/day. These losses reflect inefficiencies in electrical conversion and battery charging processes, suggesting opportunities for optimization through improved energy storage technology and more efficient energy management systems.

Unused energy due to full battery capacity (Lu), illustrated in dark blue, exhibits clear seasonal fluctuations. The lowest Lu value occurs in December at approximately 0.5 kWh/kWp/day, while the highest is observed in August, reaching nearly 1.0 kWh/kWp/day. The annual average Lu is 0.73 kWh/kWp/day. The increase in Lu during the dry season indicates that the battery storage capacity is insufficient to store all the energy produced, resulting in a portion of the surplus energy being unused.

Summing up, the three loss components (Lc, Ls, and Lu), the total average daily energy loss amounts to 2.23 kWh/kWp/day. Given that the system's total daily energy production ranges from 5.5 to 6.0 kWh/kWp/day, the energy utilization efficiency by users is approximately 60–65%. Meanwhile, the remainder is lost through system losses, Lc, and unused energy.

Overall, the data indicates that the PV system operates effectively in supplying energy, though it remains significant potential for efficiency improvements. These improvements can be achieved through enhanced PV panel design and maintenance, increased efficiency in energy conversion and battery systems, and adjustments to storage capacity to accommodate surplus energy during high-production months.

3.2. Performance Ratio (PR) and Solar Fraction

Based on simulation results, the maximum energy that can be produced by the solar panels reaches 67,661 kWh per year, with the highest monthly output of 6,194 kWh in August and the lowest of 4,992 kWh in February. From the designed components, a PR of 0.602 and a SF of 1 were obtained. This indicates that the designed system is capable of meeting 100% of the energy demand.

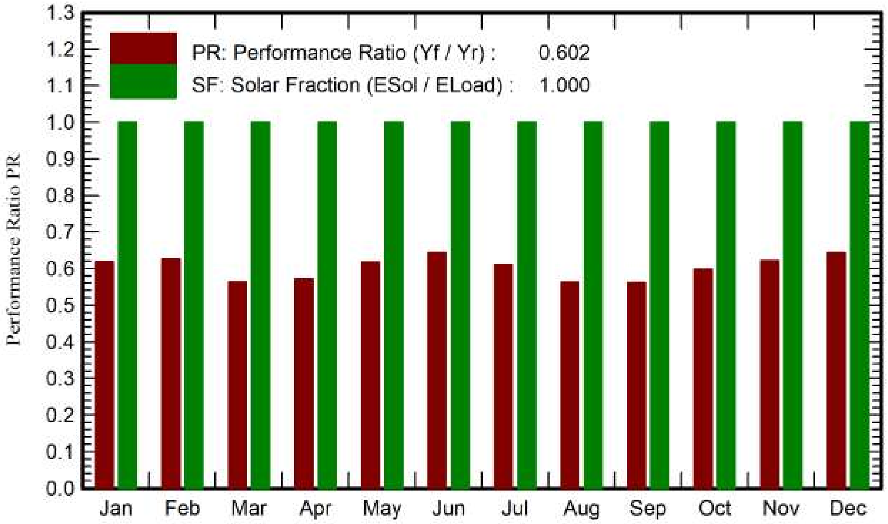


Figure 5. PR and solar fraction

Figure 5 above presents the monthly PR and SF of the SPP system in Insumbabi over a year of operation. The graph employs two key parameters to evaluate system performance: PR, represented by dark red bars, and

SF, shown by green bars. The PR is an indicator of the overall efficiency of the photovoltaic system. It reflects how much energy is delivered to the load compared to the energy that could be produced under ideal conditions. Mathematically, PR is expressed as the ratio between the final yield (Yf) and the reference yield (Yr). The average annual PR shown in the graph is 0.602, meaning that approximately 60.2% of the total available solar energy is successfully converted into electricity and supplied to the load. A relatively stable PR range between 0.55 and 0.65 throughout the year indicates consistent system performance. Even though, it is still influenced by factors such as ambient temperature, dust accumulation, module degradation, and the efficiency of the power conversion and energy storage systems.

SF is defined as the ratio of the energy generated by the PV system (Esol) to the total energy demand (Eload). The graph demonstrates a consistent SF value of 1.000 throughout the year, indicating that the PV system can fully meet the user's energy demand each month without requiring any supplementary energy sources. The constant and maximal SF value confirms that the system capacity has been adequately designed to satisfy the daily energy requirements of the user, even with seasonal variations in solar irradiance. Overall, the graph illustrates that the Insumbabi system operates reliably and efficiently in supplying user energy needs. Although the PR value suggests potential energy losses (around 40% of the reference potential), the system's performance remains within acceptable limits for an off-grid solar power system operating in a tropical region. Further optimization efforts may focus on improving power conversion efficiency, reducing array losses, and enhancing energy storage management to increase the overall PR without compromising the SF value.

3.3. Single Line Diagram Insumbabi

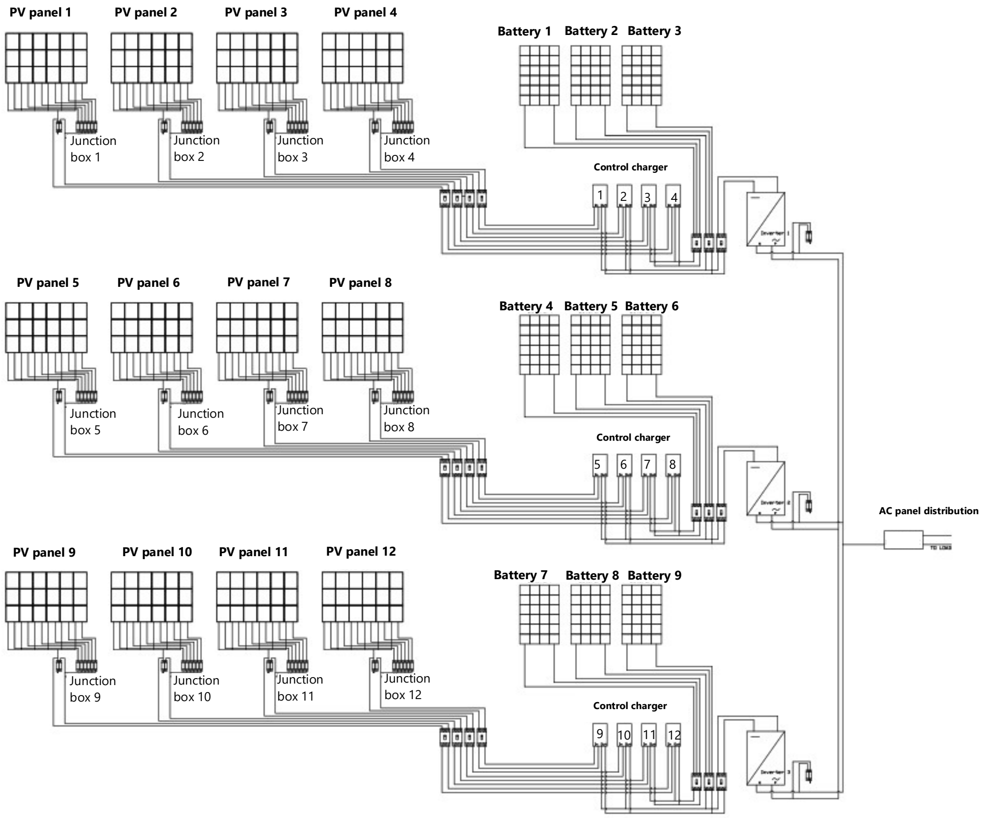


Figure 6. Single line diagram Insumbabi island

The single-line diagram of the SPP equipment on Insumbabi Island can be seen in Figure 6 below. Figure 6 shows the configuration of the main components of the SPP, from the solar panel modules to the distribution panel. A total of 216 PV modules is divided into 12 strings, with each string consisting of 18 PV modules arranged in 3 series by 6 parallel. Each string is connected to an SCC (Solar Charge Controller) to charge 216 battery units (24 series by 9 parallel) and to supply the load.

3.4. Site Plan Desgin Solar Power Plant Insumbabi

Figure 7 shows the site layout of a 40 kWp off-grid Solar Power Plant system designed to meet the electricity demand on Insumbabi Island. The site area measures 35 meters by 34 meters and is divided into two main zones: the solar panel zone and the equipment shelter zone. The solar panel zone is located on the left side of the site, consisting of 18 solar panel arrays and containing a regular grid configuration of modules. These are arranged to optimize solar radiation absorption, with orientation and tilt angles determined based on local irradiation analysis. The layout design considers the spacing between arrays to avoid shading effects between modules and allows for maintenance access pathways.

On the right side of the site, there is a shelter that houses the energy storage system (batteries), inverters, and control devices (controllers) at an elevation level of ±0.03 meters above the base surface. This shelter is connected to an access path with a lowered elevation from the local road surface to accommodate the land contour. In the center of the site, a lightning protection system is installed as part of the overall protection system to ensure the reliability and safety of the solar power plant. This layout is designed not only for energy efficiency but also incorporates considerations for safety, ease of maintenance, and protection against environmental disturbances. It reflects a systematic approach to planning renewable energy infrastructure in remote areas with challenging geographic conditions.

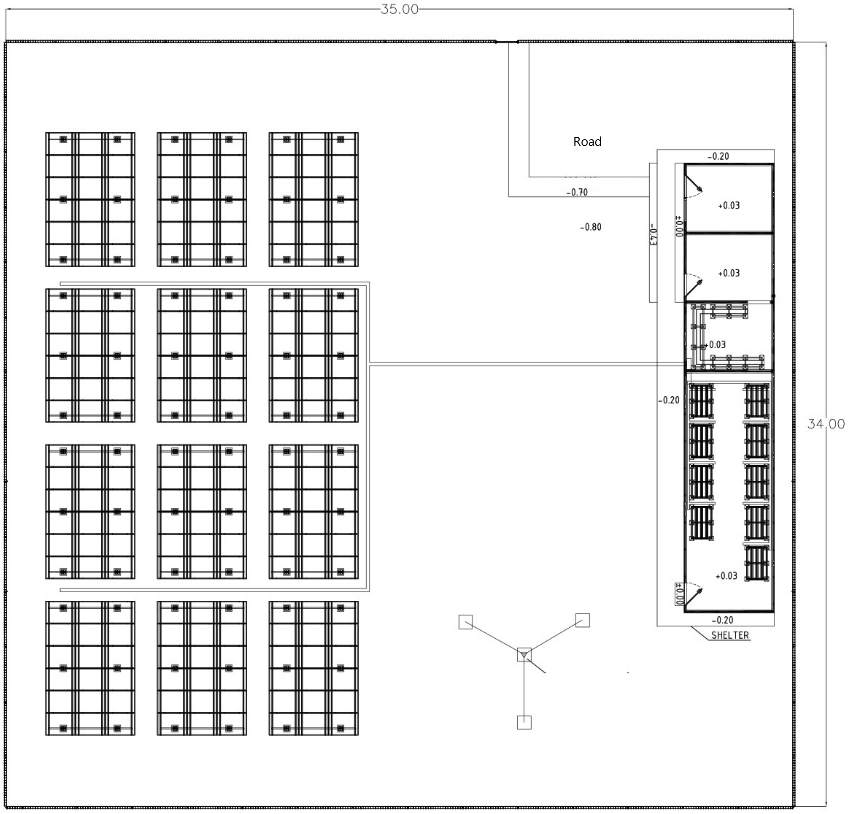


Figure 7. Site plan Insumbabi SPP

4. Conclusion

This study presents a novel design of a 40 kWp off-grid PV system for remote areas by integrating high-fidelity field data with PVsyst simulation software—an approach not previously reported in comparable research. Simulation results indicate an annual energy yield of 67,661 kWh, with a peak monthly output of 6,194 kWh in August and a minimum of 4,992 kWh in February. The system achieves an average PR of 0.602, reflecting efficiency losses attributable to temperature and weather variations. Nevertheless, a SF of unity (1.0) in every month ensures that this 40 kWp PV installation fully meets 100% of the electrical load demand of the Insumbabi Island community without reliance on a backup generator.

5. Acknowledgments

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